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SPECIAL FEATURE: ORIGINAL ARTICLE

Feasibility of Silviculture for Complex Stand Structures

Comparison of tree size structure and growth for partially harvested and even-aged hemlock-spruce stands in southeast Alaska

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Abstract The effects of partial cutting on tree size structure and stand growth were evaluated in 52 plots in 13 stands in southeast Alaska that were partially harvested 53–96 years ago and compared with 50-year-old even-aged stands that developed after clearcutting. The net basal-area growth was greater in the partially cut plots than in the uncut plots, and basal-area growth generally increased with increasing cutting intensity. However, the basal-area growth of all of the partially harvested stands was significantly less than the growth of 50-year-old even-aged stands, and net basal area growth over the 50 year period since partial harvesting was about 33–43% of the growth of the even-aged stands. Partial cutting maintained stand structures similar to uncut old-growth stands, and the cutting had no significant effect on tree species composition. The tree size distribution of the partially harvested stands was far more complex and well distributed in comparison with the 50-year-old even-aged stands, and included the presence of several trees with diameters of more than 100 cm. These trees included both large-diameter spruce and hemlock trees and were a distinctive structural feature that was noticeably lacking in the even-aged stands.

Keywords Clearcutting · Partial cutting · Southeast Alaska · Stand structure · Tree growth

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Introduction

The coastal rainforests of southeast Alaska have a simple tree species composition, including Sitka spruce [*Picea sitchensis* (Bong.) Carr.], western hemlock [*Tsuga heterophylla* (Raf.) Sarg.], and minor amounts of western redcedar (*Thuja plicata* Donn ex D. Donn), yellow-cedar [*Chamaecyparis nootkatensis* (D. Don) Spach] and red alder (*Alnus rubra* Bong.). Spruce and hemlock are the major tree species, and these two species combined comprise over 90% of the total regional growing stock (Hutchison and LaBau 1975). However, these forests have complex tree age and size structures that relate to the regional pattern of forest disturbance. The natural disturbance regime of southeast Alaska is dominated by high-frequency, low-intensity disturbance events with the development of complex multi-aged stands (Deal et al. 1991; Nowacki and Kramer 1998). Stand development after clearcutting follows a different pattern; a new cohort of western hemlock and Sitka spruce develops from the establishment of new seedlings and the release of advance regeneration. Tree density is abundant and canopy closure occurs in 15–25 years, followed by a long and intense period of stem exclusion (Alaback 1982; Deal et al. 1991). During this stage of stem exclusion, few (if any) new trees regenerate, and other understory vegetation is suppressed for up to 100 years (Alaback 1982, 1984; Tappeiner and Alaback 1989). These dense young-growth stands have uniform tree diameter and height

distributions and notably lack the multi-layered, complex size structures of old-growth forests. Forest development after clearcutting has long-term effects on reducing understory plants and significant implications for wildlife such as Sitka black-tailed deer that depend on these plants as forage (Hanley 1993). Other silvicultural systems based on partial harvesting or stand retention are being assessed to determine if there are management alternatives to clearcutting (McClellan et al. 2000).

Clearcutting with natural regeneration has been the predominant timber management practice in this hemlock-spruce forest type since the 1950s, when pulp mills were established in southeast Alaska. Today there are about 270,000 ha of young-growth even-aged stands in the region out of a timber base area of about 1.4 million ha (Barbour et al. 2005). Recent management plans have prescribed forest practices using alternatives to clearcutting (TLMP 1997; McClellan et al. 2000), and some recent studies have shown that silvicultural systems based on partial cutting could provide a sustainable timber resource while also maintaining some old-growth forest characteristics (Deal 2001; Deal and Tappeiner 2002). Partial cutting of forests was a common practice in southeast Alaska from 1900 to 1950 until pulp mills were established in the region. Large Sitka spruce trees were cut for sawtimber, or pole-sized western hemlocks were harvested for piling, leaving stands with variable density, species composition, and sizes. These stands were harvested without a planned silvicultural system to ensure tree regeneration or stand growth. Forest managers are interested in developing silvicultural solutions to increase stand structural diversity and enhance biodiversity in these forests (McClellan 2005; Deal 2007).

In a previously reported study, the effects of partial cutting on species composition, new and residual-tree cohorts, tree size distribution and tree growth were assessed in 18 stands partially harvested 12–96 years ago in southeast Alaska (Deal and Tappeiner 2002). They determined that current stand basal area and growth were dominated by residual trees left after harvesting, and that the diameter growths of Sitka spruce and western hemlock were similar. They also reported that concerns about changing tree species composition, lack of spruce regeneration, and greatly reduced stand growth and vigor with partial cuts were largely unsubstantiated (Deal and Tappeiner 2002). However, little is known about the use of silvicultural systems that use selection or partial cutting and their effects on stand dynamics, stand growth and tree size structure. To assess the impacts of partial cutting, we reanalyzed 13 of the oldest of these partially harvested stands to determine the effects of partial cutting on tree size structure and stand growth, and compared these stands with nine even-aged stands that developed after clearcutting 48–52 years ago. In particular, we were interested in comparing these partially cut stands with younger even-aged stands to determine the effects of partial cutting on stand growth over a 50-year period since harvesting, and to assess the effects of partial cutting on tree size structure.

Materials and methods

Study areas and stand selection

In 1995 and 1996, eighteen partially harvested stands were sampled that encompassed a range of times since cutting, intensities of cutting, and geographic distributions throughout southeast Alaska (Deal 2001; Deal and Tappeiner 2002). Study areas were selected using the following criteria: (1) a range of "time since cutting," from 10 to 100 years ago; (2) stands with only one partial cutting; (3) a wide range of cutting intensities at each site, including an uncut area; (4) uniform topography, soils, and forest type. All research sites were within 2 km of the shoreline and less than 100 m in elevation. At each site, an uncut control and generally three partially cut areas (light, medium, heavy) were located and 0.2 ha plots were installed in each cutting intensity area, with a total of 73 plots in 18 stands. From this former data set we selected 52 plots in the 13 stands (Fig. 1) that were partially harvested at least 50 years ago to assess stand growth and structural

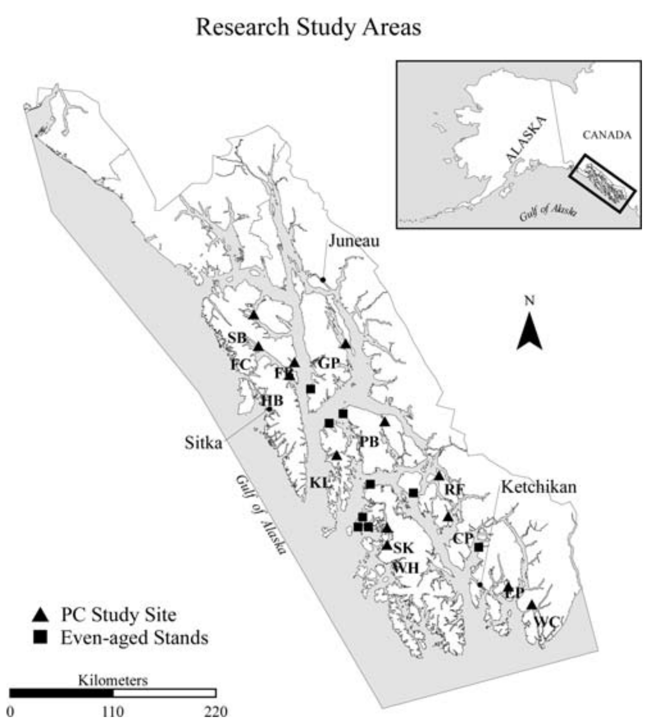

Fig. 1 The 13 partially cut (PC) study sites and nine even-aged stands in southeast Alaska. Study site letter codes for PC sites are referenced from Table 1

Table 1 Descriptions of research sites listed from the oldest to the most recently cut site

Research site	Cutting intensity				Current stand[a] composition and site information							
	Time since cut (years)	Basal area			Basal area (m^2 ha^{-1})	All trees (trees ha^{-1})	*Picea* (%)	*Tsuga* (%)	Cedar[b] (%)	Forest type	Elevation (m)	Site $index_{50}$[c] (m)
		Cut (%)	Cut (m^2 ha^{-1})	Left (m^2 ha^{-1})								
WC, Weasel Cove	96	17–51	9–23	22–45	53–75	450–1220	0–24	67–100	0–17	*Picea*	30	24
GP, Glass Peninsula	85	23–69	15–41	17–47	60–84	147–397	11–34	28–83	0–49	*Picea*	20	29
FB, Florence Bay	82	50–57	33–38	26–38	56–83	120–360	18–75	25–82	0	*Picea*	10	32
PB, Portage Bay	78	26–65	7–28	14–25	47–56	459–1202	5–33	67–95	0	*Tsuga*	35	27
KL, Kutlaku Lake	76	31–63	17–31	18–37	58–139	305–525	5–49	35–95	0–16	*Picea*	5	32
HB, Hanus Bay	73	49–96	24–85	3–25	56–83	413–1180	6–62	38–94	0	*Picea*	25	30
SK, Sarkar	70	27–59	14–28	19–37	57–76	467–1163	0–11	89–100	0	*Tsuga*	60	30
EP, Elf Point	69	17–73	12–36	13–57	42–116	453–1443	2–4	72–96	0–24	*Tsuga*	30	24
CP, Canoe Passage	68	16–75	9–57	19–46	44–66	815–2452	2–13	74–92	6–19	*Tsuga*	100	27
SB, Salt Lake Bay	67	48–55	28–35	29–31	63–87	158–642	17–73	27–83	0	*Picea*	10	30
WH, Winter Harbor	64	24–38	19–39	56–70	73–95	785–1311	2–33	67–98	0	*Picea*	5	29
FC, Finger Creek	55	18–41	11–33	44–51	58–75	331–522	5–60	40–95	0	*Tsuga*	5	30
RF, Rainbow Falls	53	34–61	15–25	16–29	44–66	348–1108	0–28	63–100	0–10	*Picea*	20	27

The cutting intensity data show the ranges for the partially cut plots at each site. The current stand data include the ranges for both the uncut and cut plots at each site. The forest type is the major overstory tree species at each site

[a] Stand data for trees and basal area include all trees that are at least 2.5 cm DBH

[b] The other minor species include western redcedar (*Thuja plicata* Donn ex D. Don) and yellow-cedar [*Chamaecyparis nootkatensis* (D. Don) Spach]

[c] Potential site index, base age 50, height (m)

changes over the initial 50-year period since cutting (Table 1).

Stand growth and structure

To describe the current stand structure, we recorded the tree diameter at 1.3 m (DBH), the height, the crown class and the species of all live trees greater than 2.5 cm DBH, and the species, the DBH and the decay class for each snag. On each plot, we reconstructed the basal area of cut trees from the stump diameter and took increment cores from 10–20 trees of each species and crown class to determine age, basal area growth, and cutting date for each stand using tree-radial growth analyses with cutting dates verified by historical data, if available (Deal 1999). We reconstructed stand structure, basal area, species composition and cutting intensity for each plot (Table 1) using site-specific regression equations (Deal 1999). We blocked by site, and compared differences in tree species composition and stand growth between cut and uncut plots using contrast analysis.

We used trees that had grown for 50 years since cutting in 13 stands cut 53–96 years ago to determine diameter distribution and frequency of western hemlock, Sitka spruce, and other minor tree species. The tree diameter at time of cutting was determined using increment cores from 712 western hemlock, Sitka spruce, yellow-cedar and western redcedar trees. We developed site-specific regression equations to predict DBH at time of cutting for all trees, relating DBH at time of cutting to current tree DBH, basal area, species, and plot cutting intensity (Deal 1999). Regression models to predict tree DBH 50 years after cutting were developed in a similar manner to the models used to predict tree DBH at cutting date. The frequencies of medium (41–70 cm DBH), medium-large (71–100 cm DBH) and large (100+ cm DBH) trees per hectare were compared for stands after cutting, before cutting, and 50 years after cutting. We tested for average frequency differences in each diameter class for stands before cutting, after cutting and in the current stands 50 years after cutting using paired-sample *t* tests.

To compare the stand growth and structure of partially harvested stands with those of even-aged stands, we selected nine permanent stand density growth plots in the hemlock-spruce forest type of southeast Alaska (DeMars 2000) that naturally regenerated after clearcutting 48–52 years ago (Fig. 1; Table 2). These stands were representative of typical even-aged stands in the region, and site indices ranged from 23 to 33 m at base age 50 and were comparable to those of our partially harvested stands (Table 1). Site index is defined here as the potential forest productivity expressed in terms of average dominant tree

Table 2 Summary of current stand and net basal area (BA) growths of partially cut [PC (heavy, medium, light, uncut), $n = 13$] and clearcut (even-aged, $n = 9$) sites 50 years after harvest

Treatment	Proportion of stand cut (%)	Current stand BA (m^2 ha^{-1})	Net BA growth since cutting (m^2 ha^{-1})	50-year net BA growth (m^2 ha^{-1})
Heavy PC	63.76	59.12	37.71	20.46
Medium PC	50.34	70.00	38.35	27.07
Light PC	31.61	72.59	35.35	20.70
Uncut	0	84.89	27.01	15.09
Lower-site PC ($n = 7$)	43.49	64.69	31.18	18.01
Higher-site PC ($n = 6$)	53.88	70.81	44.56	30.93
Even-aged ($n = 9$)	100	61.84	61.84	61.84

Lower-site PC ($n = 7$) are sites with a 50 year site index <30 m, higher-site PC ($n = 6$) $\geq$ 30 m. Even-aged stand data are from permanent plots ranging in age from 48 to 52 years (DeMars 2000); site index ranged from 26 to 33 m at a base-age index of 50 years

height at base age 50 years (Helms 1998). The stand basal areas and growths of these nine 50-year-old stands were combined and summarized (Table 2). To ensure that these nine permanent plots followed regional growth projections, we modeled and compared the growths of even-aged stands by performing bare ground growth simulations using the regional SEAPROG growth model (Dixon et al. 1992). We further divided the 13 partially cut stands into lower-site class (SI < 30 m, $n = 7$) and higher-site class (SI $\geq$ 30 m, $n = 6$) to assess if there were differences in tree size and frequency between lower-site, higher-site and even-aged stands (Fig. 2). We compared the current stand growths, tree sizes and frequency distributions of these 50-year-old even-aged stands with those of the partially harvested stands 50 years after cutting.

Results

Current stand structure of partially cut stands

Cutting intensity varied both within and among stands, ranging from an absolute basal area cut of only 7 m^2 ha^{-1} (26% of original basal area) at Portage Bay to 85 m^2 ha^{-1} (96% of original basal area) at Hanus Bay (Table 1). Some stands had higher initial basal areas and relatively high residual basal areas left after cutting (e.g., Winter Harbor), and other stands had smaller amounts of basal area cut (e.g. Kutlaku Lake, Salt Lake Bay) but grew vigorously after cutting (Table 1). Partial cutting had little effect on species composition and there were no significant differences between the cut and uncut plots in the proportions of either Sitka spruce or western hemlock trees ($P = 0.46$ and 0.84, respectively; Deal and Tappeiner 2002).

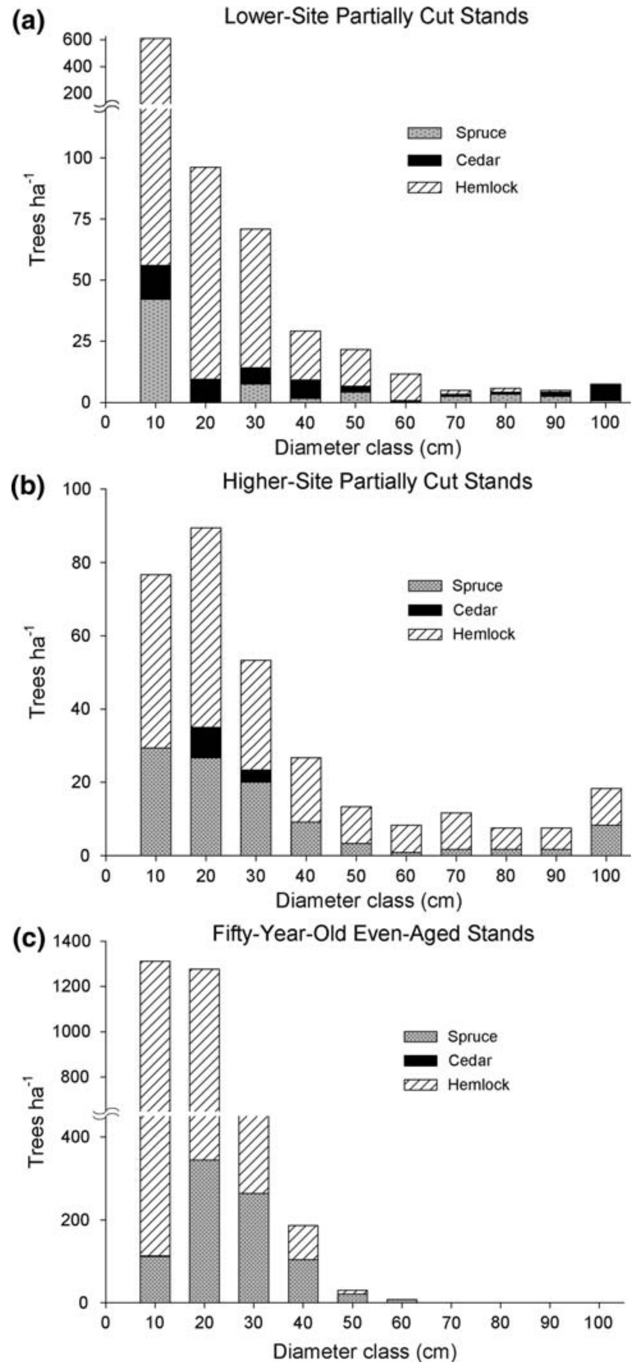

Fig. 2 Average tree diameter distributions for lower-site (<30 m) partially cut stands (**a**), higher-site ($\geq$30 m) partially cut stands (**b**), and 50-year-old even-aged stands (**c**)

Growth of partially cut and even-aged stands

The net basal-area growth was greater in the partially cut plots than in the uncut plots; however, two of the heavy

cutting intensity plots experienced considerable mortality after harvest that reduced growth averages for the heavy cutting intensity treatments (Table 2). We also found significant differences in net basal-area growth among stands ($P < 0.01$). To account for these differences, we blocked by stand and found statistically significant differences in net basal-area growth between uncut and cut plots ($P < 0.01$) and significant increases in growth with increasing cutting intensity ($R^2 = 0.640$, $P < 0.01$). In partially cut stands, most growth occurred in small-to-medium-sized trees left after logging, but the 50-year basal area growth was significantly less than the growth observed in even-aged stands ($P < 0.01$). In fact, net basal area growth in partially cut stands over the 50-year period since harvesting averaged 20–27 m^2 ha^{-1}, which was only about 33–43% of the growth in 50-year-old even-aged stands (Table 2).

Tree size distribution of partially cut and even-aged stands

At 50 years since cutting, the tree size distributions of the partially harvested stands were far more complex and well distributed in comparison with those of the 50-year-old even-aged stands. Tree diameter distributions in the lower site stands (site index <30 m) showed numerous small-diameter trees in the 10 cm size classes, several mid-sized trees of diameter 40–60 cm, and also a few larger trees in the 70–100 cm diameter classes (Fig. 2a). These stands included some newly regenerated smaller-diameter cedar trees and a few large residual cedars left after harvesting that provided large tree size structural diversity (Fig. 2a). The diameter distributions of the higher site stands (site index ≥30 m) showed fewer trees in the smallest 10 cm size class, a fairly even distribution of trees across diameters 30–90 cm, and some large-diameter trees in the 100+ size class. Almost all trees were hemlock and spruce, with only a few smaller-diameter cedar trees. In particular, the largest size class (100+ cm trees) was a significant structural component in partially cut stands (~20 trees ha^{-1}) (Fig. 2b). These trees included both large-diameter spruce and hemlock trees and were a distinctive structural feature that was noticeably lacking in the even-aged stands. The 50-year-old even-aged stands had several hundred small-diameter trees in the smallest 10–20 cm diameter classes, numerous trees in the 30–40 cm size classes, a few trees in the 50–60 cm size classes, and no trees larger than 60 cm in diameter (Fig 2c). These stands were almost entirely hemlock and spruce, with only a tiny amount of small-diameter cedar trees. These even-aged stands had relatively uniform size distributions with virtually no larger-sized trees, and this diameter distribution highlights the simple structures of these stands.

Current and former stand structures of partially cut stands

The tree frequency distribution was significantly different in stands before and after partial cutting, but these stands quickly developed complex size structures. Most of the trees harvested had a large diameter; however, some large-diameter trees (hemlock, spruce or cedar) were usually left after cutting. The number of trees in large (>100 cm), medium-large (71–100 cm) and medium (41–70 cm) diameter classes left after cutting averaged 6, 13 and 42 trees ha^{-1}, respectively (Fig. 3). Before cutting, an average of 17, 30 and 65 trees ha^{-1} were in these diameter classes, and we found significant differences ($P < 0.01$) between stands before and after cutting in the number of medium, medium-large and large diameter trees. After 50 years, however, the number of trees in these size classes was similar to the numbers found in the stands before cutting, with an average of 13, 26 and 69 trees ha^{-1} in the large, medium-large and medium-diameter classes, respectively (Fig. 3). The current stands had slightly more medium-diameter trees (+5 trees ha^{-1}) and slightly fewer medium-large (−4 trees ha^{-1}) and large diameter (−3 trees ha^{-1}) trees than the stands before cutting, but no significant differences in tree frequency were found for any diameter class ($P = 0.50$, 0.40 and 0.42, respectively).

Discussion

Growth of partially cut and even-aged stands

Partial cutting increased basal area growth relative to the uncut plots, but 50-year net basal area growth was significantly less in these partially cut stands than in the even-aged stands, with an average of 0.40–0.54 m^2 ha^{-1} $year^{-1}$. Most growth occurred on small-to-medium-sized trees left after logging, and these trees grew rapidly after partial cutting and were a significant and dominant component of the current stand. Previous analysis showed that the vast

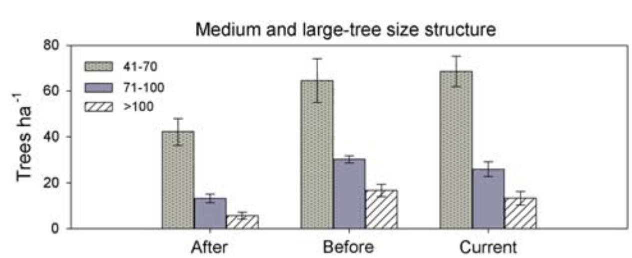

Fig. 3 The number of medium- and large-size trees per hectare by size class in the partially cut plots immediately after and before cutting, and in the current stand 50 years after cutting. *Vertical bars* indicate standard errors

majority of growth occurred on these residual trees, with 85–95% of the stand basal area growth on trees left after logging (Deal and Tappeiner 2002). The best growth also occurred in trees 20–80 cm DBH at time of logging, with an average diameter growth of 30 cm over 50 years. This is an important finding, as these larger trees are more valuable and the primary source of future timber harvests. Both western redcedar and yellow-cedar were found in some of the partially harvested stands. Cedar was a less desirable species for timber and was commonly left after harvesting, providing both some larger residual trees and a seed source for regeneration. Cedar was more commonly found in the lower-site than the higher-site stands (Fig. 2a, b). It appears to be better adapted to poorer sites than hemlock or spruce (D'Amore et al. 2009), and its higher frequency in lower-site stands may be more related to site conditions and residual trees than to partial cutting.

Conversely, we found that the vast majority of trees in even-aged stands were small-diameter trees (Fig. 2c). These small-diameter trees fully stocked the stand and contributed a significant amount of the total stand basal area. After 50 years, the even-aged stands had 2–3 times more basal area growth then the partially harvested stands (Table 2), and will eventually contribute a significant portion of the future timber supply of the region. During the past 40–50 years, nearly 270,000 ha of young-growth stands have been created from commercial timber harvesting (Barbour et al. 2005). If the primary focus of forest management in the region is wood production, then the reduced growth in partially harvested stands may be a concern. However, if management objectives include increasing stand structural diversity and enhancing other forest resources, then partial harvesting may play an important role in forest management.

Tree size structures of partially cut and even-aged stands

The residual trees remaining after partial cutting grew rapidly and are a dominant part of the current overstory stand. Immediately after cutting there were few trees on these plots greater than 70 cm DBH, and these cut stands had very different tree size structures than the old-growth stands prior to cutting (Fig. 3). Fifty years after cutting, however, these stands had similar numbers of large-sized (>100 cm DBH) trees compared with the old-growth stands, and these similar diameter distributions were largely a result of the growth of the smaller- and medium-diameter trees into the larger-diameter classes. Conversely, the even-aged stands had very homogeneous size structures, with hundreds of small-diameter hemlock and spruce trees (Fig. 2c), few mid-sized trees, and virtually no larger-sized trees. These results are particularly important because they highlight the long time frame required for trees in even-aged stands to reach large sizes and to finally replace the large-diameter trees that were cut. For example, upon modeling tree growth in even-aged stands for comparable lower and higher site classes using a bare ground starting point (Dixon et al. 1992), it was found that 280 years were needed for our higher sites and 350 years for lower sites before the unthinned stands reached 100 cm DBH—an extraordinarily long time. In our partially cut stands, nearly half of all trees that were greater than 100 cm in DBH 50 years after cutting were 70–80 cm at the time of cutting, and these medium-large trees grew rapidly following partial cutting.

The stand structures that develop after partial cutting create structurally complex, multi-layered forest canopies that are much more similar to old-growth stands than to the uniform young-growth stands that develop after clearcutting. The presence of large and small residual trees left after partial cutting creates structural heterogeneity and complex overstory–understory interactions, and these structures may be important for maintaining abundant and diverse understory plant communities. Deal (2001) reported that the species richness and abundance of understory plants were similar in partially cut and uncut plots, and that these similar plant community structures were related to the overstory stand structures. The high species richness and abundance of understory plants in partially cut stands are quite different then the typical plant understories found in stands that develop after clearcutting, and the loss of biodiversity following clearcutting is well documented in southeast Alaska (Wallmo and Schoen 1980; Schoen et al. 1988; Hanley 1993; Hanley et al. 2006).

Management implications for partial cutting in southeast Alaska

It is important to note that the stands we studied were cut to provide specific wood products such as spruce sawtimber and hemlock pilings. Cutting occurred without a planned silvicultural system, with little effort made to ensure tree regeneration, stand growth, or to maintain the complex stand structures typically found in old-growth forests. We found that these partially cut stands had similar tree size structures that were comparable to the original old-growth forest. The natural disturbance regime in southeast Alaska is characterized by high-frequency, low-magnitude disturbance events (Brady and Hanley 1984) that result in complex multi-aged or uneven-aged stands (Deal et al. 1991; Nowacki and Kramer 1998). The more complex structures left after partial harvesting may create conditions similar to natural low-intensity disturbances that are common in the region. However, the growth of these partially cut stands was significantly less than the growth of even-aged stands

over a similar time period. If the primary objective is to maximize wood production and to produce trees of a uniform size for timber, then the use of clearcutting and even-aged forest management may be appropriate. In general, stand growth response was related to the intensity of harvesting, and the best growth occurred in more heavily harvested stands. Stand growth depends on a number of factors, including intensity of cutting, site conditions, and the number and size of residual trees left after cutting. Provisional rotation periods for partial harvesting or selection cutting may be as short as one or two decades for lightly harvested stands and several decades for more intensively harvested stands. Our analysis of historical partial cutting highlights the potential of selection cutting to maintain forests with enhanced tree size complexity, including large-diameter trees, which are a distinctive structural feature that are noticeably lacking in even-aged stands. Managers need to carefully consider some of the potential tradeoffs in stand growth and wood production with the long-term maintenance of stand structural diversity and their effects on other forest resources. With careful tree selection and control of stand density, it will be possible to maintain diverse tree size structures with silvicultural systems that use partial cutting. By thoughtfully implementing normal forest management practices, new silvicultural systems could be developed to provide productive stands for timber, and also to maintain diverse stand structures that are similar to old-growth forests.

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